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Development of a Distributed Water Stress Model for Karuvannur River Basin

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Abstract

Water stress is a situation where the availability of water is a major constraint on growing water demands. In this study the water stress status of Karuvannur River Basin (KRB) is assessed in a distributed scale. It is computed on the basis of a factor called stress ratio expressed as the ratio of water demand and water availability. Therefore, connecting the quantity of water demand with the amount available can shed light to the status of the water resource and the need for further corrective action. In this study, the water stress analysis is carried out both in basin and sub-basin scale. For that, the Karuvannur river basin is divided into 11 sub-basins and their water availability is assessed based on long term rainfall-runoff simulation using Soil Water Assessment Tool (SWAT). The water availability of the basin is computed by analyzing historical data. By conducting frequency analysis, the total available water is taken as the discharge that equalled or exceeded 95% of the time. The water demand is calculated considering the domestic requirement alone. It is seen that though total available water is more than enough to meet the domestic demand of water at basin scale, water scarcity in certain areas got exposed only when the analysis is done on a sub-basin level and to a monthly time scale. Since water is sufficiently available within this basin, by implementing conservation measures within the basin, such problems can be solved. These results may also assist in planning of future water resources development and reducing the water crisis that may prevail in Karuvannur river basin due to water scarcity.

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1. Introduction

Water resources are finite in space and time. Sustainable water management in a river basin requires knowledge of water availability & water requirements of the basin in the present & future for various purposes. Conventional spatially and temporally lumped estimates of water availability do not help much in the planning & development of water resources in the watershed. Spatial variation due to distributed land use, soil texture, topography, ground water level & hydro meteorological conditions should be accounted for in the water availability estimation. The water availability and demand assessment of a basin is the key aspect in water resources development and management programmes. In this study, ArcGIS interface of SWAT is used. The water availability and demand assessment of Karuvannur river basin is carried out to evaluate the annual and monthly level water stress in both basin and sub-basin level focusing on strategies for water conservation and management. The water resource status of Karuvannur river basin in the year 2020 is forecast based on the water stress ratio.

Water scarcity is the lack of sufficient available water resource to meet the demands of water usage within a region. The overall water stress of the basin can only be obtained in a lumped scale. To get a clear picture of the spatial and temporal variation of water stress in the river basin, the problem should be analysed in a distributed level, both in spatial and temporal scale.

Shimelis B. D. et al.[1] developed a simple model to assess space–time relationships of water resource availability and demand in watersheds. The spatial and temporal distribution of water resources and the corresponding demand were quantified. Results have shown significant variability of water availability and demand in the Mara River Basin (MRB). According to Shimelis B. D. et al. [2], MRB has been maintaining the livelihood of people and pristine biodiversity from the Mau Escarpment in Kenya through Mara-Serengeti protected areas to the flood plains in Tanzania. The MRB presents a delicate balance of water utilization by human settlement and pristine biodiversity. Previous studies reported increasing pressure from population growth, expansion of agriculture and pastoral land, deforestation, urbanization and land degradation in the basin.

Hoffman et al. [3] identified six major water demand sectors Human population, Livestock population, Wildlife population, Lodges and Tent camps, Large-scale Irrigation farming and Large-scale mining and estimated their respective monthly demand volume with a cautionary notice of data insufficiency.

Bingner [4] simulated runoff for ten years for a watershed in northern Mississippi. The SWAT model produced reasonable results in the simulation of runoff on a daily and annual basis from multiple sub basins, with the exception of a wooded sub basin. Results showed a good agreement between observed and simulated runoff and sediment yield during the study period.

In this paper a novel approach is used for the assessment of water availability and demand of Karuvannur river basin on a spatial and temporal scale by dividing it into 11 sub-basins. Out of several water balance models available, SWAT model is selected and applied for this study. For the entire basin and each of the sub basins, the flow duration curves are developed and $Q_{95}$is found out and the water availability is evaluated in basin and sub-basin level. Then the water demand for domestic purpose is found both in basin and sub-basin level. The final output is the water resource status of each sub basins which clearly shows the water stress areas in the Karuvannur watershed.

2. Study Area and Data Description

The Karuvannur watershed lies between 10 ^{0} 15’ to 10 ^{0} 40’North latitude and 76 ^{0} 00’ to 76 ^{0} 35’ East longitude within Thrissur district and shares the Western boundary of Palakkad district of Kerala and thereby covers an area of 1054km^2.Karuvannur Bridge located at 10 ^{0} 24’13.84” N and 76 ^{0} 12’58.09” E is taken as the outlet for the area considered.

The ArcSWAT graphical user interface is used to manipulate and execute the major functions of SWAT model from the ArcGIS tool. The inputs required for the model are prepared as required by the ArcGIS interface of SWAT.

The model inputs required for SWAT can be broadly classified into two categories:

i. Spatial data

ii. Temporal data

The required spatial data inputs include Digital Elevation Model (DEM), land use map and soil map while the temporal daily data include air temperature both minimum and maximum, precipitation, relative humidity, wind speed and solar radiation. The census data of 2001 and 2011 of Thrissur is also required for the study.

3. Methodology

In order to find the water stress of a river basin, it is essential to find the water availability and demand of that basin. To get a clear picture of the spatial variation of water stress in the river basin, the problem should be analysed in a distributed level. So the water stress status of the river basin should be analysed in two ways:

1. Basin wise approach
2. Sub-basin wise approach

To find the water availability of the river basin, it is essential to obtain the discharge values at the outlet of the basin. SWAT model is used to model the entire watershed in order to predict the runoff values using available data. The future water availability is calculated by conducting frequency analysis with historic data. The future water demand is evaluated by projecting the present population assuming a linear growth rate.

For the frequency analysis, 20 years discharge data is generated from SWAT model. But the climatological data is available only for 10 years (2002-2011). Since the climatological data is not available for the past period from 1992-2001, its value is assumed as the average value of the data of the period from 2002-2011. The discharge generated by the model for 20 years is used for further analysis. Flow duration curve (FDC) is plotted for the whole basin. It is assumed that a flow value which is equalled or exceeded 95% of the time (Q_{95}) represents the water availability of that basin. Hence, from the flow duration curve, the volume of water available annually is computed as

$$V = Q_{95} \times \frac{365 \times 24 \times 60 \times 60}{10^6} \text{ Mm}^3$$

Domestic water demand is taken as 135 lpcd as per the recommendations of World Health Organisation. For the estimation of water requirement in the basin, it is required to find out the population in the basin from the known demographic data at Panchayat level. Therefore, the administrative boundary of Thrissur is clipped with the boundary of KRB. The percentage area of each Panchayats coming under the basin is calculated and the total population in the basin is determined on proportionate area basis of the Panchayats falling within and outside the boundary.

In order to throw light on to water stress in the coming future, the water demand is estimated for a projected population in 2020. To estimate the forecasted population of 2020, the census data of 2001 and 2011 are used and assumed a linear growth rate.

The water stress of the river basin is calculated as the ratio of estimated values of water demand and availability. From the stress ratio values of the river basin, the water resource status of the basin can be found out.

The water resource status (WRS) is determined from the following relation

- WRS = 0 ; SR ≤ 10% (Low Stress)
- WRS = 1 ; SR = 10 - 20% (Medium Stress)
- WRS = 2 ; SR = 20 - 40% (Medium-High Stress)

- WRS = 3 ; SR > 40% (High Stress)

  (Source: WMO)

Basin level water stress assessment gives only a lumped idea about the water resource status of the river basin. In order to find out the spatial variability of water stress, the basin is divided into sub-basins and the sub-basins are analysed individually.

For the easiness in calculating the population of each sub-basin from the known population of administrative areas, the basin is divided into sub-basins giving due consideration to the administrative boundaries. For this, the administrative boundary of Thrissur is clipped with the boundary of the watershed and the percentage area of all Panchayats coming inside each sub-basin is calculated separately. An assumption is made such that the percentage of population of each Panchayats coming in each sub-basin is taken in proportion to the percentage area of Panchayats in the respective sub-basins. The total projected population of each sub-basin is calculated from the demographic data. The cumulative water demand is then computed for each sub-basin at the rate of 135lpcd.

The discharge value of each sub-basin is generated from SWAT model. In order to calculate the water availability of each sub-basin, annual flow duration curves are plotted and the value of Q_{95} are taken from the graph. The water availability is calculated by the same procedure explained above. After obtaining the values of water availability and demand, the water stress and hence the water resource status of the sub-basin is found out as explained above.

4. Analysis and Results

Water stress of Karuvannur river basin is assessed using a distributed model. On the basis of administrative boundary and hydrologic factors such as land use and soil, Karuvannur river basin is divided into eleven sub-basins. The quantity of available water at basin level and sub-basin level is estimated through hydrological simulation. The demand of water (particularly domestic use only) is calculated at basin and sub-basin level. Then the water resource status is found out by calculating the water stress by both basin level and sub-basin level approach. It is done on annual as well as monthly basis.

The water resource status is determined for the entire basin both annually and monthly. For this, annual and monthly FDCs are prepared separately and the value of Q_{95} is determined from the respective FDCs.

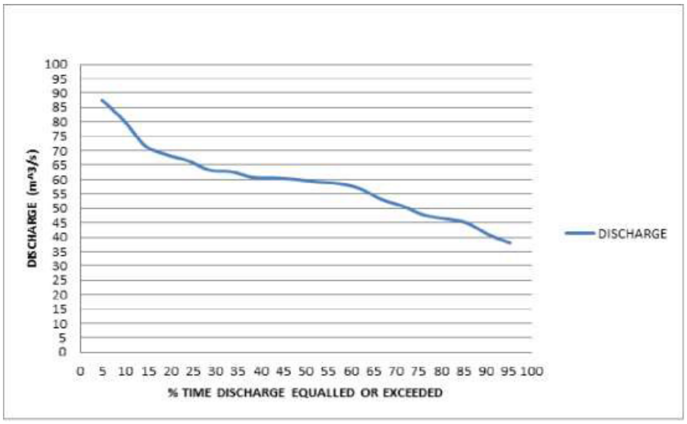

Fig.1. Annual FDC of Karuvannur watershed

The water availability, demand and thereby the water stress on annual time scale are calculated and the results are shown in Table 1.

Table 1. Overall water stress of KRB on annual basis for the year 2020

WATER AVAILABILITY(Mm^3)	**WATER DEMAND(Mm^3)**	**STRESS RATIO**	**WATER RESOURCE STATUS**
1206.3	29.72	0.02	LOW

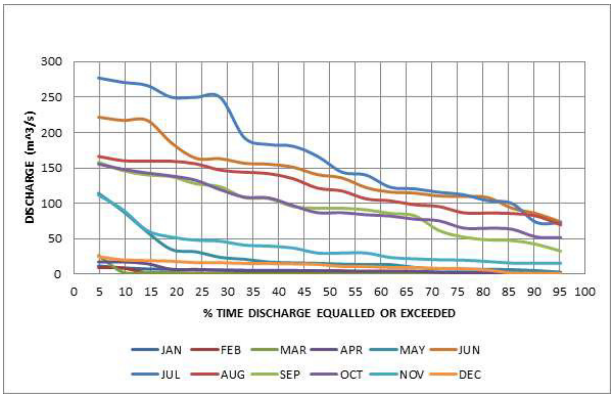

Fig.2. Monthly FDC of Karuvannur watershed

In order to determine the water demand on monthly time scale, the Panchayat area falling in the basin is delineated. The water availability, demand and thereby the monthly water stress are calculated and the results are shown in Table 2.

Table 2. Water stress of KRB on a monthly time scale for the year 2020

MONTH	WATER AVAILABILITY	WATER DEMAND	STRESS RATIO	WATER RESOURCE STATUS
JAN	1.74	2.52	1.45	HIGH
FEB	0.74	2.35	3.21	HIGH
MAR	0.53	2.52	4.75	HIGH
APR	2.11	2.44	1.16	HIGH
MAY	8.71	2.52	0.29	MEDIUM
JUNE	193.25	2.44	0.01	LOW
JULY	195.02	2.52	0.01	LOW
AUG	188.49	2.52	0.01	LOW
SEPT	85.95	2.44	0.03	LOW
OCT	138.86	2.52	0.02	LOW
NOV	40.59	2.44	0.06	LOW
DEC	3.12	2.52	0.81	HIGH

The spatial variability of water stress is hidden in the basin wide approach. So in order to get a clear idea about the spatial variability in water stress the stress analysis is carried out on a sub-basin scale.

The division of administrative areas falling in each sub-basin is shown in Fig.4.3. The projected population of the year 2020 is worked out for each sub-basin. Since the basin is well simulated in arcSWAT, the discharge of each sub-basin is obtained by running the model at sub-basin level. By conducting frequency analysis on these data, FDCs are drawn for each sub-basin both on annual as well as monthly time scale and the water availability is estimated as Q_{95} for each sub-basin. The annual water stress estimated for each sub-basin is shown in Table 3.

Table 3. Spatial variability of water stress on annual basis for the year 2020

SUB-BASIN	WATER AVAILABILITY(Mm^3)	WATER DEMAND(Mm^3)	STRESS RATIO	WATER RESOURCE STATUS
A	182.098	1.72	0.01	LOW
B	178.031	1.65	0.01	LOW
C	364.243	3.42	0.01	LOW
D	103.959	1.75	0.02	LOW
E	515.471	6.12	0.01	LOW
F	97.0955	1.01	0.01	LOW
G	664.522	9.32	0.01	LOW
H	373.197	12.48	0.03	LOW
I	1048.96	22.22	0.02	LOW
J	154.906	7.3	0.05	LOW
K	1206.3	29.72	0.02	LOW

The monthly water demand is calculated by the same procedure. To determine the water demand on monthly time scale, the Panchayat area falling in each sub-basin is delineated and shown in Fig.3.

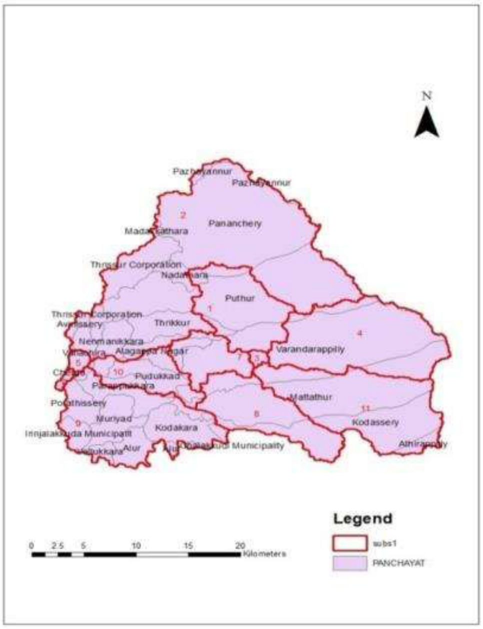

Fig.3. Map showing the Panchayats in each sub-basins of KRB

The cumulative water availability and cumulative water demand in each sub-basin is calculated on a monthly time scale. The water availability, demand and thereby the water stress on monthly time scale are calculated. The value of stress ratio can be used to find the water resource status of each sub-basin shown in Fig.4. From the water resource status values, the water deficit and surplus areas can be identified.

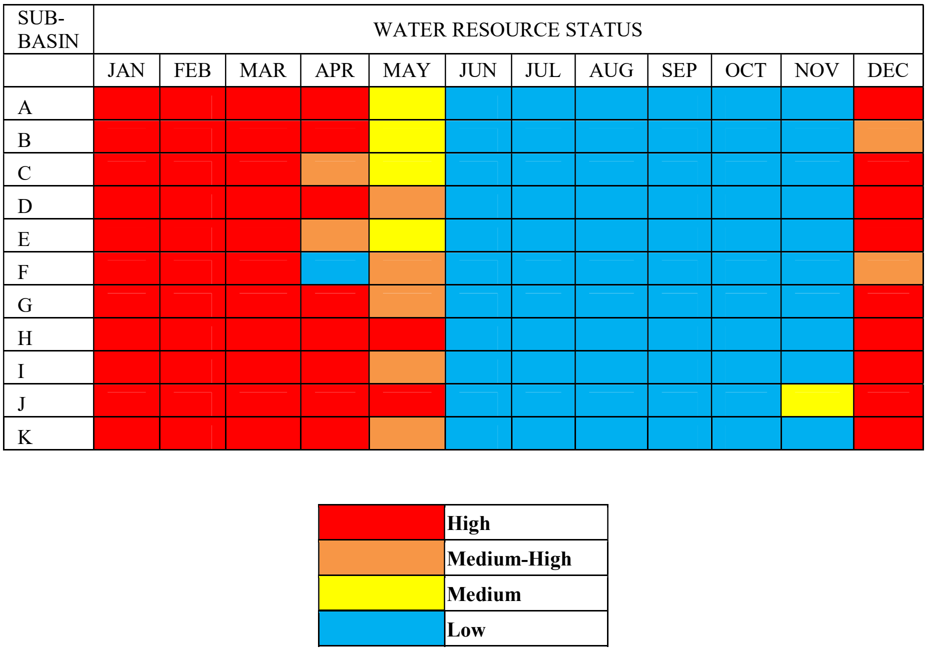

Fig.4. Monthly water resource status of each sub-basin for the year 2020

From the above results, it is found that the basin experience high water stress in the months December, January, February, March and April. There is no stress for five months namely June, July, August, September and October in any of the sub-basins. In the month of November, only sub-basin J experiences a medium stress. But all the sub-basins experience high stress in summer months. So, conservation measures are essential in all areas which can be implemented locally. Sub-basins H and J have the worst condition and hence special attention must be given for these areas. Hence, results of this study may assist in planning of future water resources development for reducing water crisis that may prevail in KRB.

5. Conclusion

From the analysis done on annual scale both on basin and sub-basin level, it is seen that it doesn't experience water stress as the annual available water is much more than the annual demand. However the analysis done on the monthly time scale exposed the temporal variation in availability and demand. The basin experiences water stress in some months all throughout the area. Further analysis on sub-basin level has really thrown light into the spatial and temporal variability of water stress. There exists large variability in water stress spatially in Karuvannur river basin (KRB) even though the total water available is more than sufficient to meet the domestic requirements on an annual basis. It is also evident that the temporal variability in available water causes water stress in the region. Spatial analysis indicates that there is no water stress in any part of the basin on annual scale. Since sufficient water is available, it can be concluded that water conservation measures within the basin can help in solving the problem of water scarcity. Spatial and temporal analysis only could reveal the real problems of water stress in the basin and throw light into the water conservation measures to be taken. It is found that almost all parts of the area experiences water scarcity. Findings of the study will assist in sub-basin wide allocation and distribution of the water resource among water surplus and scarce areas of the KRB to promote development and sustainability. Hence, results of this study may assist in planning of future water resources development for reducing water crisis that may prevail in KRB. Water demand for domestic purpose only is considered in this study due to lack of data. So the actual water resource status of the area may be much worse than the predicted results

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